Phosphorus Utilization in Feeds on a Digestible Basis for Swine and Poultry

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Take-Home Message

For the formulation of diets that more accurately match phosphorus requirement of swine and poultry with dietary supply as well as proper quantification of excretion of phosphorus for environmental considerations, the use of relative available phosphorus as a currency is nebulous. In the 11th revised edition of the nutrient requirements of swine (NRC, 2012), standardized total tract digestible phosphorus was adopted as the currency for expressing the requirements of pigs for phosphorus as well as the utilized phosphorus in feeds. There is no difference between ileal and total tract digestibility of phosphorus in swine hence the adoption of standardized total tract digestibility. In poultry however, because of the contribution of urine phosphorus to the excreta in total tract consideration, ileal digestible phosphorus is more appropriate than total tract phosphorus as a response criterion. The research community is encouraged to generate more data on ileal digestibility of feed ingredients for poultry and that the feed industry and formulating nutritionists move away from available to ileal digestible phosphorus in diet formulation for poultry.

Introduction

Digestible phosphorus represents that portion of dietary phosphorus that can be used in the body of the animal. For efficient production of animal products, it is required that the right amount of nutritionally adequate feedstuff is supplied to the animal. To achieve this goal, the digestion characteristics and utilization of such feedstuff should be well understood (Adeola, 2012). Available phosphorus in feedstuffs has been historically determined using the slope-ratio bioassay, which involves expression of response criterion to increasing concentrations of phosphorus from a test feedstuff relative to that from a reference source. The slope-ratio bioassay commonly engages a common-intercept multiple linear regression procedure. The relative available phosphorus obtained from the assay is highly dependent on, among others, the available phosphorus in the reference source and the response criterion; and the measure is not usually additive in mixed feeds. The most common response criteria are bone ash, phosphorus concentration, or breaking strength, which tend to be labor-intensive and expensive, and very importantly do not provide estimates of the quantity of phosphorus voided by animals. The use of digestible phosphorus in place of relative available phosphorus overcomes some of the issues listed above.

Functions of Phosphorus in the Body

Phosphorus is an essential mineral element, for which most vertebrate animals have a dietary requirement second only to calcium. Satisfactory growth performance, reproduction, and well-being of animals are dependent upon adequate dietary supply of phosphorus. Approximately 75% of the body phosphorus is stored in the skeleton as a principal component of hydroxyapatite, the major building block of bone. Skeletal phosphorus not only functions as the framework around which the body is constructed, but also as a reservoir of phosphorus from which the body draws for the roles it plays in almost every aspect of metabolism. These include serving as components of nucleic acids like DNA, RNA, and ATP; in high-energy compounds like phosphoenolpyruvate, 1,3-bisphosphoglycerate, and creatine phosphate; in phosphorylated proteins where it is serves in enzyme regulation; as well as in phospholipids such as phosphoglycerides, and sphingomyelin.

There is a common metabolic link between calcium and phosphorus in the means by which each mineral is regulated. Three hormones involved in the delicate regulation of these minerals are parathyroid hormone, 1,25-dihydroxycholecalciferol; the active form of vitamin D, and calcitonin (Bronner, 1997). In general, parathyroid hormone and 1,25-dihydroxycholecalciferol modulate plasma calcium and phosphorus in the following manner. Hypocalcemia leads to an increase in parathyroid hormone release which then stimulates production of 1,25-dihydroxycholecalciferol by the kidney. Ultimately, uptake of dietary calcium from the gastrointestinal tract, increased reabsorption in the renal distal tubules and calcium release from bone serve to increase plasma calcium. Concurrently, parathyroid hormone induces phosphaturia by reducing reabsorption in the renal proximal tubules to maintain proper plasma calcium to phosphorus ratio. In contrast, elevated levels of calcium serve to reduce parathyroid hormone release and 1,25-dihydroxycholecalciferol production thereby attenuating hypercalcemia by reversal of the aforementioned paths. Calcitonin works in a similar manner to reduce plasma calcium though in response to more extreme hypercalcemic conditions.

Phosphorus absorption occurs throughout most of the small intestinal tract with greatest absorptive capacity occurring in the jejunum (Berner, 1997; Bronner, 1997). Paracellular movement of phosphorus occurs throughout the small intestine, generally above the saturable concentrations of active mechanisms, and movement in this manner is not acutely regulated. However, transcellular movement of dietary phosphorus against its electrochemical gradient occurs mainly by way of Na-dependent and absorption of dietary phosphorus in this manner requires energy expenditure for the Na-P cotransport mechanism.

Forms of Phosphorus in Feeds

Phosphorus in feeds exists in inorganic and organic forms, which affect the proportion in feeds that is digestible. The inorganic sources of phosphorus include monosodium phosphate, potassium phosphate, and mono-, di-, and tri-calcium phosphates. Meat and bone meal is also a source of inorganic phosphorus. All these inorganic sources have varying proportions of digestible phosphorus (Cromwell, 1992) and the phosphorus in calcium phosphates may vary depending on specific form and degree of hydration (Eeckhout and DePaepe, 1997). The organic form of phosphorus in plants is phytin, myo-inositol 1,2,3,4,5,6-hexakis (dihydrogen phosphate) complexed with mixed cations such as Ca, Zn, Mg, and Cu. Phytin occurs mainly in seeds as a mixed salt of mainly Mg, Ca, and K (Selle et al., 2000). Phytin, the collective term used for this mixed salt (Odani et al., 1997), constitutes up to 3% of many of the oilseeds and cereals used in the animal feeds (Reddy et al., 1982, Anderson, 1985). Phytate phosphorus constitutes 50-80% of the total phosphorus in most pig and poultry feedstuffs of plant origin. Suggested roles for phytates in plants include: a reserve of P and inositol; a regulator of level of inorganic phosphate; an immobilizer of cations needed to control cellular processes and then releasing them later during germination; an energy reserve; a competitor of ATP during its rapid biosynthesis when the seed nears maturity, when metabolism is inhibited and dormancy is induced (Cosgrove and Irving, 1980).

Swine and poultry utilize phosphorus in feeds to varying extents due to the factors such as forms, degree of hydration, processing, etc., described above. Because dietary phosphorus supply does not guarantee total utilization (including digestion, absorption, and metabolism), determination of the utilized portion of the dietary phosphorus supply is essential. The currency for expressing the utilized phosphorus should also be used in expressing the requirements for phosphorus.

Phosphorus Utilization AND Requirement on a Digestible Basis

Phosphorus in feeds utilized by pigs and poultry determined by slope ratio is almost universally referred to as relative available phosphorus. More commonly, the determination of available phosphorus uses bone ash, bone phosphorus concentration, or bone breaking strength, and less regularly weight gain or feed efficiency as response criteria in slope ratio assays. Available phosphorus determined is relative because response to increasing concentrations of phosphorus from test ingredients is expressed relative to the response to increasing concentrations of phosphorus from a reference source. As such, available phosphorus estimates in feed ingredients obtained by this method depend primarily on the chosen reference phosphorus source as well as the criteria of response. Furthermore, relative available phosphorus estimates are usually not additive in diets. Furthermore, available phosphorus data give no information on the quantity voided in feces. These present a compelling line of reasoning for a move toward expressing utilization and requirement on a digestible basis.

When measured in pigs, total tract digestibility of phosphorus in feed ingredients and mixed feed is not different from ileal digestibility. This is supported by several lines of evidence. Bohlke et al. (2005) showed that apparent total tract digestibilities of phosphorus in low-phytate corn, conventional corn or soybean meal were not different (less than 3 percentage points) from apparent ileal tract digestibility of phosphorus as shown in Table 1. In low-phytate and conventional soybean meal varieties, Dilger and Adeola (2006a) observed that true total tract digestibility of phosphorus, determined by the regression method was not different from true ileal digestibility of phosphorus (Table 1). Total tract digestibility of phosphorus in canola meal was not different from ileal digestibility. A broad conclusion is that, in pigs, utilization of phosphorus in feeds and requirement for the same can be expressed on a total tract digestible basis. Apparent total tract digestible phosphorus can be corrected for basal endogenous losses to derive estimates of standardized total tract digestible phosphorus.

Because excreta in birds comprise feces and urine, total tract utilization of phosphorus, in addition to digestibility reflects post-absorptive utilization. Dietary supply of phosphorus and calcium relative to requirement and body status will affect total tract utilization. The difference between total tract utilization and ileal digestibility of phosphorus in several studies, some of which are presented in Table 2, aptly illustrate this point. In individual feed ingredients and mixed diets, total tract utilization of phosphorus is substantially different from ileal phosphorus digestibility. Based on these and several other data that portray a similar trend, utilization of phosphorus in feeds and requirement for the same in birds should be expressed on an ileal digestible basis. Furthermore, apparent ileal digestible in feeds and requirement for the same in birds should be expressed on an ileal digestible basis and apparent digestible phosphorus can be corrected for basal endogenous losses to derive estimates of standardized ileal digestible phosphorus.

Table 1. Comparative total tract and ileal digestibilities of phosphorus in some swine studies

Reference	Ingredient	Total tract digestibility, %	Ileal digestibility, %
Bohkle et al., 2005[1]	Low-phytate corn	55	57
Bohkle et al., 2005[1]	Conventional corn	29	28
Bohkle et al., 2005[1]	Soybean meal	38	37
Dilger and Adeola, 2006a[2]	Low-phytate soybean meal	63	63
Dilger and Adeola, 2006a[2]	Conventional soybean meal	45	44
Adeola (unpublished)[2]	Canola meal	35	36
Favero et al. (unpublished)[1]	Soybean meal	31	33
Favero et al. (unpublished)[1]	Soybean meal + Phytase	54	64
Diet	Low-phosphorus mixed diet	51	48
Adeola (unpublished)[2]	Canola meal	35	36

[1]Expressed as apparent digestibility
[2]Expressed as true digestibility derived from regression approach

Table 2. Comparative total tract utilization and ileal digestibility of phosphorus in some poultry studies

Reference	Ingredient	Total tract utilization, %	Ileal digestibility, %
Adedokun et al., 2004[1]	Low-phosphorus mixed diet	43	29
Dilger and Adeola, 2006b[2]	Low-phytate soybean meal	77	94
Dilger and Adeola, 2006b[2]	Conventional soybean meal	60	94
Jendza et al., 2006[1]	Low-phosphorus mixed diet	59	52
Nyannor et al., 2008[1]	Low-phosphorus mixed diet	45	30
Iyayi et al., 2013[2]	Black-eyed Pea	10	29
Iyayi et al., 2013[2]	Black-eyed Pea + Phytase	61	83
Adeola (Unpublished)	Canola meal	39	66
Iyayi et al., 2013[2]	Peanut flour	74	67
Iyayi et al., 2013[2]	Peanut flour + Phytase	84	75
Liu et al., 2013[2]	Soybean meal	54	45

[1]Expressed as apparent digestibility
[2]Expressed as true digestibility derived from regression approach

Correcting Apparent Digestible Phosphorus for Endogenous Losses

The outflow of phosphorus in the feces, excreta or at the terminal ileum contain phosphorus from dietary origin as well as various endogenous compounds such as digestive secretions and sloughed-off epithelial cells. Those of endogenous compounds in the feces or at the terminal ileum constitute the endogenous phosphorus losses that are affected by anti-nutritional factors, dry matter intake and fiber contents in the diet. These endogenous phosphorus losses may be divided into basal and specific losses, the sum of which equals total endogenous phosphorus losses. The basal losses are related to the dry matter intake but independent of the type of feedstuff or diet. On the other hand, the specific losses are related to the composition of the feedstuff or diet and therefore induced by specific feed ingredient characteristics such as contents and types of fiber, anti-nutritional factors, and level of dietary phosphorus. Digestible phosphorus contents of feeds that are not corrected for basal or total phosphorus losses are termed apparent digestible phosphorus.

Diets devoid of phosphorus have been used to determine basal total tract endogenous losses of phosphorus (Stein et al., 2006; Widmer et al., 2007). The correction of apparent digestible phosphorus for basal endogenous phosphorus losses gives standardized digestible phosphorus. The determination of total endogenous phosphorus losses and correction of apparent digestible phosphorus for total endogenous phosphorus losses gives true digestible phosphorus. However, determination of total endogenous phosphorus losses is fraught with several technical and methodological challenges.

Estimating phosphorus digestibility in feed ingredients using regression analysis mutes correction for endogenous losses. Because the use of regression method requires at least three levels of phosphorus from the feed ingredient being tested, there is additional labor and expense involved compared to single point assay for apparent digestibility estimate. The major advantage is that the regression method give a robust estimate of phosphorus digestibility that does not require correction for endogenous losses of phosphorus. Regression-derived estimates of total tract digestibility of phosphorus in some feed ingredients for pigs are shown in Table 1. Due to the issues of discussed above relative to voiding of feces and urine together in the excreta for poultry, ileal digestibility of phosphorus is measured and regression-derived estimates of ileal digestibility of phosphorus in some feed ingredients for broiler chickens are shown in Table 2.

For example in pigs, Akinmusire and Adeola (2009) reported the results of 2 studies with growing pigs using the regression analysis technique to estimate the true total tract digestibility of phosphorus in canola and soybean meals, and quantify the contribution of microbial phytase on true digestibility of P in these oilseed meals. Regression of digestible P intake response of pigs on varying levels of P intake from canola meal or soybean meal without or with added phytase at 1,000 FTU/kg is shown in Figure 1 (Adeola and Applegate, 2010). True P digestibility estimate of 34% for canola meal for the diet without phytase was lower than the 61% true P digestibility estimate for the diet with added phytase. True P digestibility estimate for soybean meal without phytase at 41% was different from that with added phytase at 71%. From these studies, the addition of microbial phytase at 1,000 units/kg improved true digestibility of P in canola and soybean meals by 78 and 73%, respectively. For a soybean meal sample that contains 6.2 g total phosphorus /kg, the phytase-related improvement in true total tract digestible is 29 percentage points, which translates to an equivalency value of 1.8 g/kg for 1,000 FTU/kg.

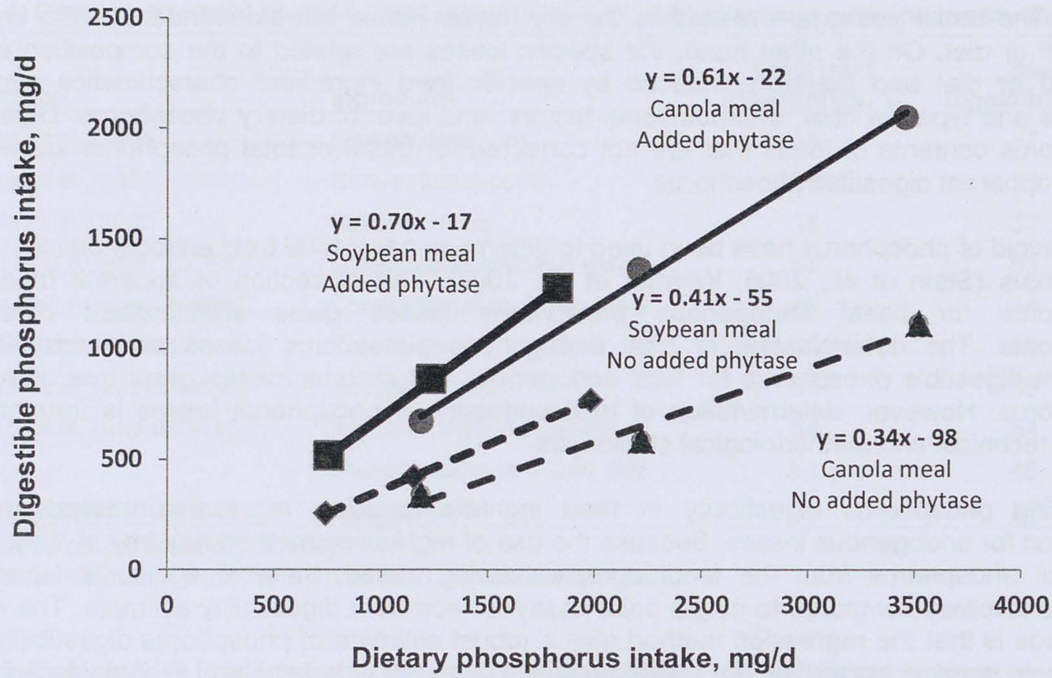

Figure 1. Regression of digestible phosphorus intake response of pigs on varying levels of P intake from canola meal (triangles) or soybean meal (diamonds) without or with added phytase at 1,000 FTU/kg (circles for canola meal with phytase and squares for soybean meal with phytase). Added phytase increased true digestibility coefficient of phosphorus (slope of the regression) from 0.35 to 0.61 in canola meal and from 0.41 to 0.70 in soybean meal (Adapted from Akinmusire and Adeola, 2009).

Approach Adopted in the 11th Revised Edition of the Nutrient Requirements of Swine NRC (2012)

In the recently published 11th revised edition of the nutrient requirements of swine (NRC, 2012), standardized total tract digestible phosphorus was adopted as the currency for expressing the requirements of pigs for phosphorus as well as the utilized phosphorus in feeds.

A modeling approach was used to generate factorial estimates of standardized total tract digestible phosphorus requirements of swine in NRC (2012). The concept of standardized total tract digestibility of phosphorus was used to reduce the impact of dietary phosphorus level on the total tract digestibility of phosphorus. The contributors to standardized total tract digestible phosphorus requirements are: (1) maximum phosphorus retention rates in the body, as a function of changes in phosphorus; (2) basal endogenous fecal phosphorus losses, as a function of feed dry matter intake; (3) minimum urinary phosphorus losses, as a function of body weight; (4) marginal efficiency of using standardized total tract digestible phosphorus intake for phosphorus retention; and (5) phosphorus requirements for maximum growth performance as a proportion of requirements for maximum whole body phosphorus retention.

Maximum whole-body phosphorus mass is clearly and closely related to whole-body protein mass and are derived from the equation: Maximum whole-body phosphorus mass (in grams) = 1.1613 + 26.012 × whole-body protein mass (in kilograms) + 0.2299 × whole-body protein mass^2. Based on a review of the literature and observations on pigs fed phosphorus-free diets the basal endogenous fecal phosphorus losses are estimated to be 0.19 g per kg dry matter intake and a value of 0.007 g per kg body weight was used as minimal urinary losses that contribute to maintenance P requirements (NRC, 2012). Adjusting nutrient balance observations on individual growing pigs for between-animal variability groups of pigs, a value of 0.77 was used as the marginal efficiency of using standardized total tract digestible phosphorus intake for whole body P retention. In the model, it is assumed that phosphorus requirements for maximum growth performance are equivalent to 0.85 of phosphorus requirements for maximum whole body phosphorus retention. Thus, standardized total tract digestible phosphorus requirements (g/day) = 0.85 × [(maximum whole-body phosphorus retention ÷ 0.77) +(0.19 × feed dry matter intake) + (0.007 × body weight)].

For utilized phosphorus in feeds, NRC (2012) provided both apparent total tract digestibility and standardized total tract digestibility of phosphorus in the feed ingredient composition tables. Apparent total tract digestibility coefficient of phosphorus (ATTDcP) is [Phosphorus intake (in grams) – Fecal Phosphorus output (in grams)] ÷ Phosphorus intake (in grams). Correction of the apparent total tract digestibility coefficient of phosphorus for basal endogenous fecal phosphorus losses (BEFPL) gives standardized total tract digestibility coefficient of phosphorus (STTDcP) as {ATTDcP + [BEFPL (in grams/kilogram of dry matter intake) ÷ Feed phosphorus concentration (in grams/kilogram of dry matter)]}. A constant value of 0.19 g per kg dry matter intake was used as the basal endogenous fecal phosphorus losses in deriving standardized total tract digestibility of phosphorus in the feed ingredient composition tables (NRC, 2012).

References

Adeola, O. 2012. Exogenous phytase and its use in low-phosphorus feeding. Proceedings of the Manitoba Swine Seminar. February 2012. Volume 26, 9 Pages 133-148.

Adedokun, S.A., J.S. Sands, and O. Adeola. 2004. Determining the equivalent phosphorus released by an Escherichia coli derived phytase in broiler chicks. Canadian Journal of Animal Science. 84: 437 – 444.

Adeola, O. and T.J. Applegate. 2010. Phosphorus and calcium equivalency of phytase. Proceedings of the 1st International Phytase Summit September 2010. Pages 45-64.

Akinmusire A.S. and O. Adeola. 2009. True digestibility of phosphorus in canola and soybean meals for growing pigs: Influence of microbial phytase. Journal of Animal Science. 87: 977-983.

Anderson, P.A. 1985. Interactions between proteins and constituents that affect protein quality. In: Digestibility and amino acid availability in cereals and oilseeds (eds Finley, J.W. and D.T. Hopkins), pp 31-45, American Association of Cereal Chemists Inc., St Paul, MN.

Berner, Y.N. 1997. Phosphorus. In: Handbook of Nutritionally Essential Mineral Elements, edited by B. L. O'Dell and R. A. Sunde. New York, NY: Marcel Dekker, Inc.

Bohlke, R.A., R.C. Thaler, and H.H. Stein. 2005. Calcium, phosphorus, and amino acid digestibility in low-phytate corn, normal corn, and soybean meal by growing pigs. J. Anim. Sci.83:2396-2403.

Bronner, F. 1997. Calcium. In: Handbook of Nutritionally Essential Mineral Elements, edited by B.L. O'Dell and R.A. Sunde. New York, NY: Marcel Dekker, Inc.

Bohlke, R.A., R.C. Thaler, and H.H. Stein. 2005. Calcium, phosphorus, and amino acid digestibility in low-phytate corn, normal corn, and soybean meal by growing pigs. Journal of Animal Science. 2005. 83:2396–2403.

Boling, S.D., M.W. Douglas, M.L. Johnson, X. Wang, C.M. Parsons, K.W. Koelkebeck, and R.A. Zimmerman. 2000. The effects of dietary available phosphorus levels and phytase on performance of young and older laying hens. Poultry Science. 79:224-230.

Bronner, F. 1997. Calcium. In: Handbook of Nutritionally Essential Mineral Elements, edited by B. L. O'Dell and R. A. Sunde. New York, NY: Marcel Dekker, Inc.

Cosgrove, D.J. and G.C.J. Irving. 1980. Inositol phosphates. Their chemistry, biochemistry and physiology. Elsevier Scientific Publishing, Amsterdam, The Netherlands.

Cromwell, G.L. 1992. The biological availability of phosphorus in feedstuffs for pigs. Pig News and Information 13:75N.

Dilger, R.N. and O. Adeola. 2006a. Estimation of true phosphorus digestibility and endogenous phosphorus loss in growing pigs fed conventional and low-phytate soybean meals. Journal of Animal Science. 84:627-634.

Dilger, R.N. and O. Adeola. 2006b. Estimation of true phosphorus digestibility and endogenous phosphorus loss in growing chicks fed conventional and low-phytate soybean meals. Poultry Science. 85:661-668.

Eeckhout, W. and M. DePaepe. 1994. Total phosphorus, phytate-phosphorus and phytase activity in plant feedstuffs. Animal Feed Science and Technology. 47: 19-29.

Eeckhout, W., and M. de Paepe. 1997. The digestibility of three calcium phosphates for pigs as measured by difference and by slope- ratio assay. Journal of Animal Physiology and Animal Nutrition 77:53-60.

Iyayi, E.A., F. Fru-Nji, and O. Adeola. 2013. True phosphorus digestibility of black-eyed pea and peanut flour withoutor with phytase supplementation in broiler chickens. Poultry Science. 92: (In press)

Jendza, J.A., R.N. Dilger, J.S. Sands, and O. Adeola. 2006. Efficacy and equivalency of an Escherichia coli¬-derived phytase for replacing inorganic phosphorus in the diets of broiler chickens and young pigs. Journal of Animal Science. 84: 3364 – 3374.

Liu, J.B., D.W. Chen, and O. Adeola. 2013. Phosphorus digestibility response of broiler chickens to dietary calcium-to-phosphorus ratios. Poultry Science. 92: (In press)

NRC. 2012. Nutrient Requirements of Swine. 11th ed. National Academy Press, Washington, DC.

Nyannor, E.K.D. and O. Adeola. 2008. Corn expressing an Escherichia coli-derived phytase gene: Comparative evaluation study in broiler chicks. Poultry Science 87: 2015-2022.

Onyango, E.M., M.R. Bedford, and O. Adeola. 2005. Efficacy of an evolved Escherichia coli phytase in diets for broiler chicks. Poultry Science. 84: 248-255.